Circuits and Resistivity

"Look for knowledge not in books but in things themselves."

W. Gilbert

OBJECTIVES

To learn the use of several types of electrical measuring instruments in DC circuits. To observe the I-V characteristics of some devices. To see how resistivity is measured.

THEORY

Because electrical devices and measurements are so pervasive, some knowledge of them is essential to all technical disciplines. In this experiment we will introduce several instruments and use them to measure the electrical characteristics of some common components and circuits. We will also measure a fundamental property of materials, the resistivity.

Circuits

An electrical circuit is a collection of components connected together with wires to perform a desired function. The physical realization of the circuit can vary enormously, as long as the connections between components are correct. For this reason, circuits are usually represented by schematic diagrams whose geometry need not resemble that of the physical circuit at all. An amplifier, for example, might equally well be assembled from several centimeter-sized components connected by pieces of solid copper wire, or from a micron-scale pattern of thin metal and semiconductor films on the surface of a silicon wafer. Details of the geometry only become important when the wavelength of the signals becomes comparable to the circuit size, typically at frequencies of a few gigahertz.

A typical schematic diagram is shown in Fig. 1, along with a picture of one possible realization. If you wanted to construct a circuit you would first identify the various components

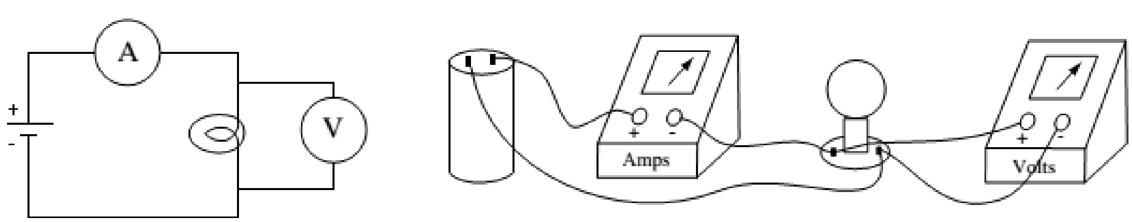


Fig. 1 Circuit for measuring the I-V characteristic of a light bulb, drawn as a schematic and as a pictorial.

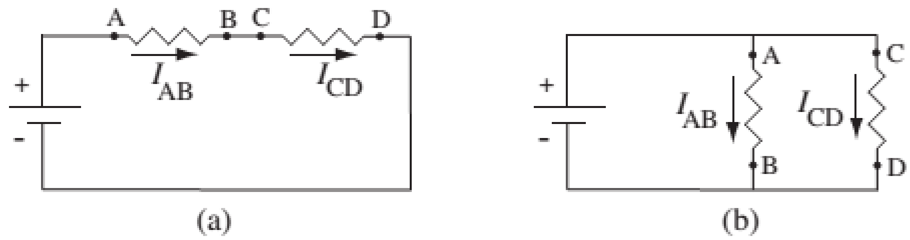


Fig. 2 (a) Series connection of DC supply and two resistors. Here $I_{AB} = I_{CD}$, but $V_{AB} \neq V_{CD}$ unless the resistances are equal. (b) Parallel connection of two resistors across a DC supply. Now $V_{AB} = V_{CD}$, but $I_{AB} \neq I_{CD}$ unless the resistances are equal.

and their connection points, using the manufacturers' data sheets if needed. You would then use wires to systematically join each component to the others according to the lines in the schematic drawing. **The relative positions of the components need not resemble the schematic layout, the circuit will work as long as the connections are correct.**

In discussing circuits, there are two general arrangements that are referred to by name, as drawn in Fig. 2 using resistors. In the series circuit the currents I_{AB} and I_{CD} must always be the same, since charge cannot accumulate between the components. The electric potential difference between A and B, V_{AB}, will not be the same as V_{CD} unless the elements are identical. For the parallel connection, the reverse is true: $V_{AB} = V_{CD}$ because they are connected by a resistanceless wire, but the currents I_{AB} and I_{CD} are generally different. The distinction is useful if, for example, you want the same current to flow in two coils to generate a magnetic field. Connecting them in series guarantees that this will occur, regardless of the characteristics of the individual coils. Conversely, a group of devices which require the same voltage, such as light bulbs, would be connected in parallel with the power source.

Using these ideas, your text derives the effective resistance of series and parallel combinations of resistors R_1 and R_2, arriving at

$$R_{eff} = R_1 + R_2 \qquad \text{(series)} \qquad (1)$$

and

$$\frac{1}{R_{eff}} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \text{(parallel)} \qquad (2)$$

More complicated combinations can be worked out by successive applications of these two results.

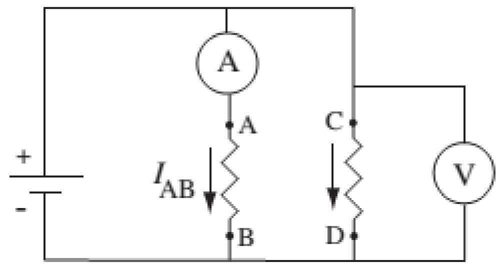


Fig. 3 Resistors connected in parallel across a DC supply. The ammeter is placed in series with one resistor to measure I_{AB}, while the voltmeter is placed in parallel with the other resistor to measure V_{CD}.

Electrical meters

The potential difference between two points in a circuit can be measured with **a voltmeter connected in parallel** between the points, as shown in Fig. 3. An ideal voltmeter would have infinite resistance so that current flow in the circuit will not be affected by the additional path between the measuring points. Practical voltmeters, or the voltage input to a computer interface, have resistances of 1 MΩ - 10 MΩ, which may affect measurements in circuits with other large resistances.

Current flow through a specified part of the circuit is measured by inserting **an ammeter in series** at the desired location, as shown in Fig. 3. An ideal ammeter would have zero resistance so the circuit would not be affected by insertion of the meter. Depending on their design and sensitivity, practical ammeters will add their internal resistance of 1 -10 Ω into the circuit, which may disturb low-resistance circuits. Incidentally, their low resistance also means that if an ammeter is connected directly across a source of voltage, such as a battery, a very large current will flow. This is likely to damage both the source and the meter.

Meters are also available to determine DC resistance. They typically apply a known voltage to the component to be tested and measure the resulting current, displaying the ratio as the resistance in ohms**. The component must be disconnected from the rest of the circuit to avoid interference from currents or voltages not supplied by the meter.**

I-V characteristics and resistivity

One of the most basic properties of any electrical device is the amount of current I which flows when a known voltage V is applied to the device. A plot of the current as a function of the voltage is usually called the I-V characteristic of the device. The I-V characteristic is often a complicated curve, which may change as the temperature of the device changes, as light hits the device and so on. Sometimes these changes are used to sense temperature, light level or some other variable, but at other times any change is a nuisance. Whatever the I-V curve looks like, it is customary to define the ratio V/I as the resistance, R, of the device at a particular current, temperature, light level etc. When V is in volts and I in amperes, R is in ohms.

There are many situations in which the I-V curve is simply a straight line through the origin. In other words, $V = IR$, where R is a constant. Such devices are said to obey Ohm's Law, or to be "ohmic". If the curve is also reasonably independent of external influences the device becomes particularly useful in electronics, and is simply called a "resistor". For example, in later experiments it will be convenient to use the voltage across a known resistor to infer the current in a circuit.

Resistance depends on both the geometry of the device and the material of which it is made. The resistivity is a more fundamental property of the material, since it is independent of the geometry of a particular specimen. Resistivity, ρ, is defined by

$$\rho = E/j \tag{3}$$

where j is the current density in response to an applied electric field E. More practically, the measured resistance of a sample of length L and area A is related to the resistivity by

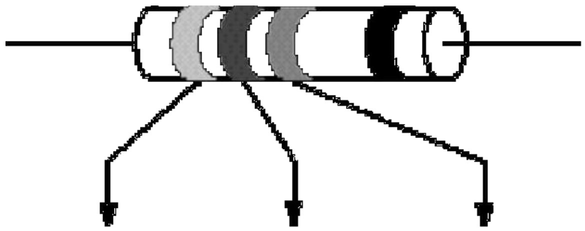
$$\rho = RA/L \tag{4}$$

<u>This relationship assumes that the material has been shaped into a uniform cross-section and that the current is uniformly distributed across the area.</u>

When used in circuits, any combination of ohmic resistors is also ohmic, and could be replaced by an equivalent single resistor according to the rules for series and parallel combinations.

EXPERIMENTAL PROCEDURE

Your lab station is equipped with a panel of mounted components, an adjustable voltage source, an analog ammeter, a digital multimeter (DMM) and wires for easily connecting things. For this experiment we will use only the light bulb and the resistors on the panel. Connections are made to the terminals beside each component. The resistors are identified by their values in ohms, using an archaic color code which is explained in Fig. 4, and posted at the front of the lab room. The voltage source is usually referred to as a power supply. It contains circuitry which converts household power to an adjustable DC voltage. Connections are made through the terminals on top, and the desired output is set with the multi-turn knob. The black terminal is the ground of the power supply. The ammeter is to be connected in series into a circuit.



Color	Digits		Multiplier
Black		0	10^0
Brown	1	1	10^1
Red	2	2	10^2
Orange	3	3	10^3
Yellow	4	4	10^4
Green	5	5	10^5
Blue	6	6	10^6
Violet	7	7	10^7
Gray	8	8	10^8
White	9	9	10^9

Fig. 4 The resistor color code. The last band specifies the relative accuracy of the value: Gold ±5%; Silver ±10%; No band ±20%. A 51kΩ, 10% resistor would be marked Green-Brown-Orange-Silver.

Three sensitivity ranges are available on the ammeters for this lab. Which sensitivity range is used by the ammeter is determined by which red terminal is connected into the circuit.

Figure 5 illustrates the style of DMM used in the lab, with important features labeled. The function dial is used to select the type of measurement and sometimes the range, although many DMMs select the scale automatically. An input terminal usually labeled COM or Common is the reference for most measurements. The other terminals may be labeled with various combinations of **V**, **A** and **Ω**, indicating their use for measuring voltage, current and resistance respectively. Wires from these terminals are connected into the circuit as needed for each function. Additional labels on the same or other terminals may be used to denote the inputs for other functions such as high current, high voltage, capacitance or frequency ranges when those are present.

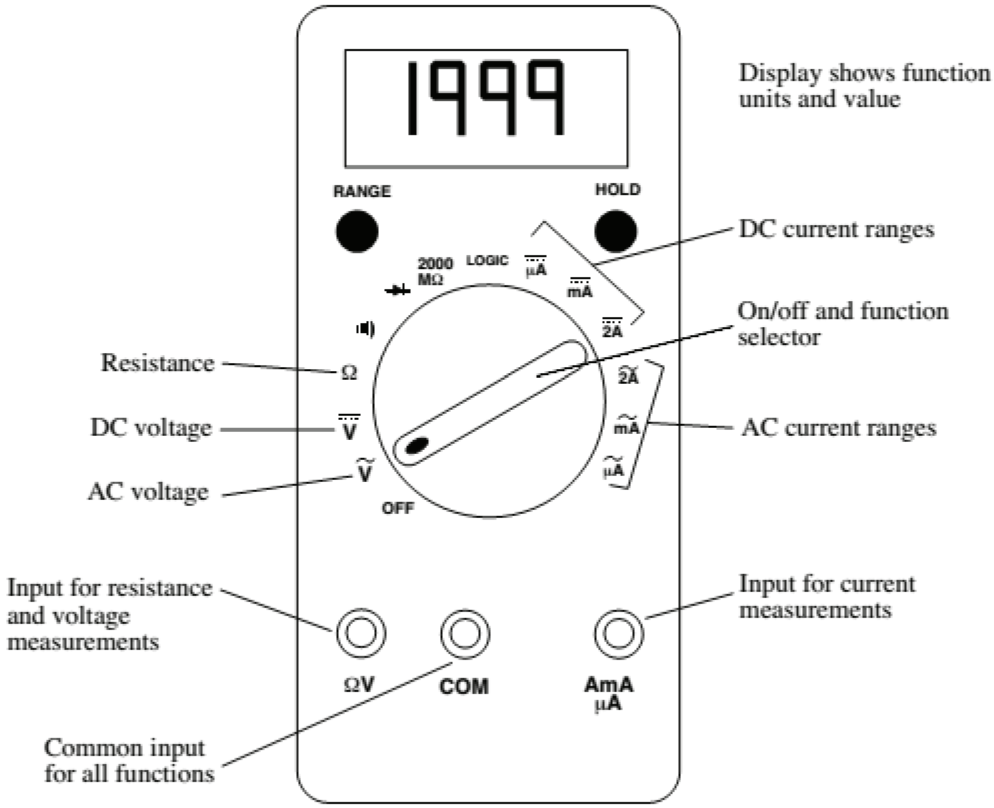


Fig. 5 Controls and inputs for a general-purpose DMM typical of those used in the lab.

I-V measurements

The first experiment you should try is the measurement of the I-V characteristic of a resistor. Wire up the circuit of Fig. 1, **replacing the light bulb with a 150Ω resistor and the battery with the power supply**. A diagram is placed on your table that identifies each element on the large circuit broad. Use the DMM to measure the voltage across the resistor. By varying the output of the power supply you will vary the current through the resistor. Using *LoggerPro*, plot current vs voltage as you go along to avoid the tedium of tabulating and then plotting data. Is the inverse of the slope of your proportional fit line reasonably close to 150Ω?

When you finish with the resistor, replace it with the light bulb, and make a similar plot. **Be sure to include the full range of voltage from less than 1 volt to close to 10 volts. Measure at least three data points between 0 volt and 1 volt and at least two data points above 8 Volts.** Note that the temperature of the filament affects the resistance of the bulb. Is the lamp ohmic?

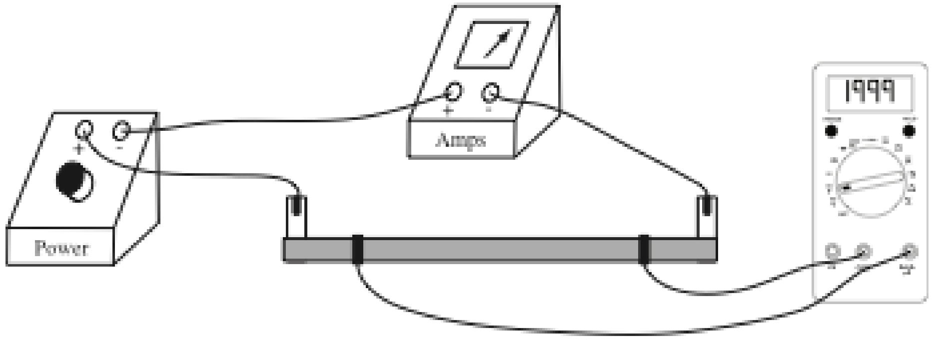


Fig. 6 Circuit for measuring the resistance of Play-Doh. Current is supplied through flat copper plates at the ends of the shape. Voltage is measured between probes resting lightly on the surface, a distance *L* apart.

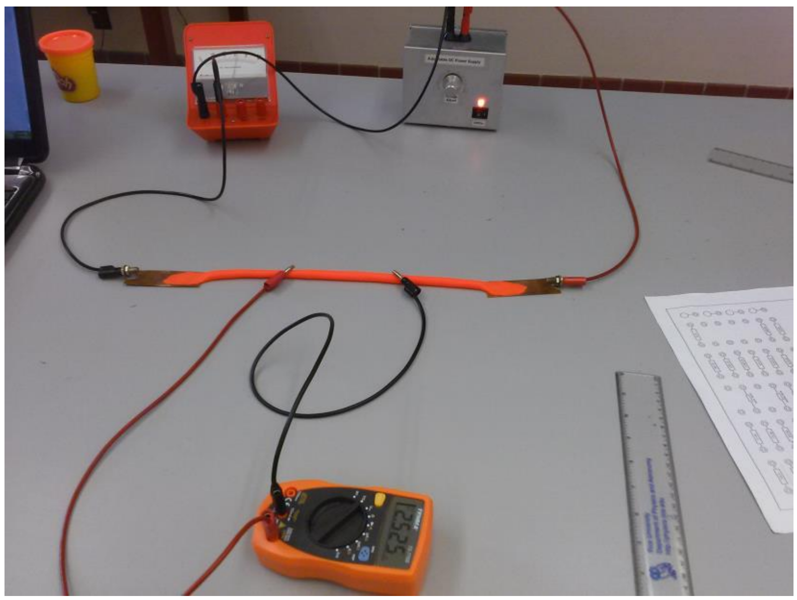


Fig. 7 A photo of what the Play-Doh circuit should actually look like. Note the “4-probe” configuration of the measurement.

Bulk resistivity

Next we will determine the electrical properties of some Play-Doh™. Because it does not come with wires attached, we will need to make our own connections. This is a bit complicated because chemical reactions between metal and Play-Doh may cause the contact resistance to change as current flows. **To get around this problem, we will make a “4-probe” measurement as sketched in Fig. 6.** The purpose of the “4-probe” measurement is to ensure that the positions on the Play-Doh where the voltage difference is measured are physically separated from where the current flow into the Play-Doh. **You MUST measure the resistance of the Play-Doh using the circuit described on Figure 6 and 7.** Roll out a circular cylinder of Play-

Doh, keeping the diameter as uniform as possible, and press the ends onto the two copper plates provided. Don't worry about deforming the Play-Doh at the ends. Make sure there is good contact between the Play-Doh and the copper plated. **Make the specimen long and skinny** so the voltage will be big enough to measure easily. Connect the copper plates in series with the ammeter and power supply so you can pass current through the sample. Measure the voltage between two points a convenient distance apart on the cylinder surface, taking care not to deform the material too much. **The connection from the voltmeter MUST NOT be connected to the copper plates. They should be far away from the copper plates.** Changes in resistance at these contacts cannot affect the voltmeter reading since there is no current flow through the voltage contacts. Determine an I-V curve characteristic for your Play-Doh cylinder, and decide whether or not Play-Doh is ohmic.

Knowing the current, voltage and geometry you can derive the resistivity of Play-Doh from **Eq. 4.** **When calculating the resistivity of Play-Doh, the relevant length to use in the experiment is the distance between the voltage probes, NOT the total length of the Play-Doh.** Find the resistivity for the cylinder and for **Two other** cylindrical (LONG AND SKINNY) Play-Doh objects with non-circular cross-sectional shapes to see if the resistivity is indeed a constant of the material. For consistent measurements, the distance between the voltage probes should be the same for all three Play-Doh objects you measured. **You DO NOT need a full I-V curve for every shape if you already know the material is Ohmic based on your observation with the circular cross-section cylindrical Play-Doh object.**

Resistor combinations

As a last exercise, you should **use the ohmmeter capability of the DMM** to check the rules for series and parallel combinations of resistors, Eq. 1 and 2. Pick any two resistors from the **left-hand column on the panel** to be R_1 and R_2, and measure their values with the DMM. Are they within the specified tolerance of their marked values? Using the measured values, calculate the effective resistances for the series and parallel combinations of the two resistors. Measure the actual series and parallel resistances. Do the measurements agree with the calculation?